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Insightful, Comprehensive application-based Overview of Nanosensors

Madhuri K. Patil*[1], Manoj V. Girase[2], Amod S. Patil[3], Nitin G. Haswani[3], and Arun M. Patil[4]

[1]R.C. Patel English Medium Junior College, Shirpur Dist. Dhule (MS) 425 405

[2]Department of Pharmacognosy, R.C. Patel Institute of Pharmaceutical Education and Research, Shirpur, Dist. Dhule (MS), India 425 405

[3]Department of Pharmaceutical Chemistry, R.C. Patel Institute of Pharmaceutical Education and Research, Shirpur, Dist. Dhule (MS), India 425 405

[4]Department of Physics, R.C. Patel Arts, Commerce and Science College, Shirpur Dist. Dhule (MS) 425 405

Abstract:

Nanosensors have emerged as a promising technology in various fields, offering valuable insights into the detection and monitoring of a wide range of substances at the nanoscale. Nanosensors have gained significant attention in the field of sensing applications due to their unique physicochemical properties that are dependent on their size at the nanometer scale. These materials, with their distinct characteristics, hold great promise for various sensing applications. The nanosensor exhibits the capability to transmit data and information pertaining to the behaviour and characteristics of particles at the nanoscale, while manifesting this information at the macroscopic level. Nanoparticles exhibit distinct chemical, mechanical, and optical characteristics that render them highly suitable for deployment in nanoscale sensor applications. In this discourse, we shall delve into the advancements witnessed over the course of recent years pertaining to nanosensors, which have exhibited diverse applications.

Keywords: Nanoscience; Nanotechnology; Nanosensors etc.

Introduction:

In recent decades, there has been a notable growth in the global market for nanosensors. The utilisation of nanosensors in medical diagnostics and various other devices has been observed as a noteworthy advancement within the industry. Furthermore, this technique finds application in the field of structural design, where it can be effectively utilised on a macroscopic level. In the realm of environmental chemistry, the utilisation of nanomaterials has emerged as a promising approach for monitoring various pollutants. This innovative strategy enables environmental chemists to achieve enhanced cost-effectiveness, efficiency, and selectivity in their monitoring endeavours [1-3]. Furthermore, an increased surface area within a chemical sensor leads to heightened exposure and detection capabilities, particularly when it comes to detecting trace amounts of the target molecule. The inherent fragility of nanomaterials gives rise to a heightened degree of susceptibility. The increased surface area of these entities contributes to their enhanced efficiency and durability. Nanosensors often utilise various types of nanoparticles, including silver nanoparticles, platinum nanoparticles, and palladium nanoparticles. Nanomaterials possess the ability to be readily manipulated, with their size, structure, and composition collectively influencing their properties. Extensive testing has been conducted on nanosensors, leading to their widespread adoption within our

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civilization. These sensors are utilised in various gadgets that are prevalent in our surroundings [4,5].

The surface characteristics of the nanomaterial utilised in colorimetric tests serve a significant role in determining the analytical performance of nanosensor systems [6,7]. Two potential solutions to this challenge are electromagnetic and chemical nanosensors. Electromagnetic nanosensors are capable of detecting alterations in electromagnetic waves, incorporating the principles of quantum phenomena. Conversely, molecular nanosensors possess the ability to convert biological communication systems into encoded messages. Mechanical nanosensors have the potential to serve as a power source for molecular nanosensors by harnessing energy obtained from the vibration of nanosensors and surrounding biochemical material [8, 9].

The development of nanosensors indicates, with the capacity, to link nanodevices exponentially. The global nanosensors market is projected to reach $1,321.30 million by 2026, to register a CAGR of 11.0% during the forecast period. The nanosensors market encompasses the production and application of physical, chemical, and biological systems and devices at scales ranging from individual atoms or molecules to around 100 nanometers. Nano Sensor carries a significant impact and serves as a revolutionary and beneficial technology across various industrial domains, including communication, medicine, transportation, agriculture, energy, materials & manufacturing, consumer products, and households [10].

This paper discusses introductory part of nantechnology, nanosensors, types of nanosensors and recent applications and advancements of nanosensors, their sensing techniques and advancements.

Nanoscience and Nanotechnology

The term "nano" finds its etymological roots in the Greek language, specifically derived from the word "nanos," which translates to "dwarf" in English. In the context of measurements, "nano" signifies the numerical value of one-billionth, denoting a fraction of a whole that is exceptionally minute. The unit of length in question is commonly referred to as a nanometer (nm), denoted as 1×10^{-9} m.

Nanoscience, a scientific discipline, focuses on the study of matter that exists in close proximity to or slightly above the atomic and molecular scale. This field investigates materials that possess distinctive electrical and chemical characteristics, particularly at dimensions smaller than 100 nm.

Nanotechnology, as an interdisciplinary field, encompasses various aspects of applied science and engineering. Its primary focus lies in the exploration of the design, synthesis, characterization, control, manipulation, and application of materials, devices, and systems at the nanoscale. The nanoscale refers to dimensions ranging from 1 to 100 nanometers, or alternatively, materials and structures possessing at least one physical dimension smaller than 100 nanometers [11].

The object of interest can be visualised as being approximately 0.5-1 micrometres in diameter, which is roughly one hundred-thousandth the size of a typical human hair. The dimensions of a bacterium, which represent the threshold of visibility under conventional optical microscopes, approximate 1 μm (equivalent to 1000 nm). The dimension of 100 nm

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corresponds to the approximate scale of a virus, which is approximately one-tenth the size of a typical bacterium.

The investigation of matter at nanoscales reveals distinct properties compared to its bulk state. Nanotechnology focuses on exploring extraordinary phenomena and intriguing characteristics that emerge due to the reduced dimensions. In this context, the field under consideration pertains to the expansion of the natural sciences, namely physics, chemistry, and biology, into the realm of nanoscale dimensions. The field of nanosciences encompasses various sub-disciplines, including nanophysics, nanochemistry, nanobiology, nanoelectronics, nanomechanics, nanomachining, and nanomaterials.

The objects under study in nanotechnology are the *nanomaterials*, also called *nanostructured materials* [12]. Nanomaterials occur in elemental and also in composite form as compounds or their mixtures and alloys.

Nanomaterials are divided into three main classes

(i) *Nanoparticles or Zero-dimensional (0D) nanomaterials*, for example, atom clusters with particle diameter below 100 nm e.g. metallic nanoparticles, e.g., Au, Ag, and Fe

(ii) *One-dimensional (1D) nanomaterials* such as nanowires, nanotubes, and nanocables having a width less than 100 nm e.g. Carbon nanotube, silicon nanowire

(iii) *Two-dimensional (2D) nanomaterials* like nanofilms and superlattices with layer thickness in the nano-range e.g. Metallic, semiconducting or insulating films [13].

Difference between Sensors and Transducers

The etymology of the term "sensor" can be traced back to its linguistic origins in ancient Greek. Specifically, the word "sensor" is derived from the Greek word "sentire," which conveys the concept of perceiving or sensing. The device under consideration is capable of transforming various forms of physical stimuli, including mechanical motion, heat, light, sound, and magnetic or electric or radiant effects, into an electrical signal. This electrical signal can then be quantified or documented by an observer or an instrument. The utilisation of this particular entity encompasses a wide range of objectives, encompassing both the quantification of phenomena and the transmission of data or knowledge [14].

The mercury-in-glass (Hg-in-glass) thermometer is an instrument that utilises the principle of thermal expansion and contraction of a liquid to measure temperature. This device consists of a glass tube that is calibrated and filled with mercury. As the temperature changes, the mercury expands or contracts, causing it to rise or fall within the glass tube. The position of the mercury within the calibrated scale allows for the determination of the temperature. The process of temperature conversion to an output voltage is facilitated by a device known as a thermocouple. This device is capable of generating an electrical potential difference, which is directly proportional to the temperature being measured. The resulting voltage is subsequently measured using a voltmeter, allowing for accurate temperature determination.

The term "transducer" can be traced back to its etymological roots in the Greek language, specifically the word "transducere," which translates to "lead across." The device under consideration is typically an electrical, electronic, electromechanical, electromagnetic, photonic, or photovoltaic apparatus that facilitates the conversion of power from one system

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to another, irrespective of whether the systems involved are identical or distinct in nature. A transducer is a device that undergoes actuation through the input of energy from one system, subsequently providing energy, typically in a different form, to a second system.

The motor is an exemplary device that effectively transforms electrical energy into mechanical energy, thereby functioning as a transducer. The loudspeaker, also known as a transducer, is a device that converts electrical energy signals into acoustic energy, commonly referred to as sound energy. The ultrasound transducer is a device that facilitates the conversion of electrical signals into ultrasonic waves, or conversely, the conversion of ultrasonic waves into electrical signals. In a similar vein, it is worth noting that a light emitting diode (LED) is capable of transforming electrical energy into light energy. [15].

In the context of sensing technology, it is important to distinguish between sensors and transducers. While both play crucial roles in converting physical phenomena into measurable signals, they exhibit distinct characteristics. Specifically, a transducer is responsible for transforming one form of energy into another, whereas a sensor primarily focuses on converting received signals into electrical form exclusively. This differentiation underscores the fundamental dissimilarity between these two The collection of information from the real world is facilitated by a sensor. According to scientific literature, a transducer is a device that exclusively facilitates the conversion of energy from one form to another. Certain devices, such as the microphone, possess the capability to function in dual roles. The thermostat within a residential refrigerator operates by utilising temperature as the input parameter, which subsequently triggers a mechanical response by means of unfurling a bimetallic strip. This action, in turn, rotates a dial that has been precisely calibrated to indicate temperature measurements in specific units. The transduction of thermal energy into mechanical motion occurs when the thermal energy corresponding to a particular temperature is converted. Contrary to popular belief, it is worth noting that a significant number of devices do not fulfil the dual functions of both a sensor and a transducer. The photoresistor is a passive electronic component that exhibits a change in resistance in response to incident light, without undergoing any energy conversion processes. One plausible approach for discerning between sensors and transducers is to adopt a nomenclature that designates the term "sensor" specifically for the sensing component in isolation, while reserving the term "transducer" for the sensing component in conjunction with its accompanying circuitry. The concept of a transducer can be understood as the combination of a sensor and an actuator. According to existing knowledge, it can be stated that transducers invariably consist of a sensor component. It is worth noting, however, that while sensors are commonly found within transducers, this relationship is not absolute and exceptions may exist. Given that transducers are devices that convert one form of energy into another, it is logical to infer that they typically incorporate sensors to detect and measure the input energy. Consequently, it can be deduced that nanotransducers, being a subset of transducers, would similarly encompass nanosensors to fulfil their intended function at the nanoscale. [16].

Necessity of Nanoscale Measurements

Upon careful consideration, it becomes apparent that both macro- and microsensors exhibit numerous limitations. The applicability of these entities is limited across various scenarios. The utilisation of compact and lightweight sensors plays a crucial role in the development of

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portable instruments. These instruments hold significant importance in various domains, including military and aerospace applications, as well as mobile and handheld consumer products.

As an illustrative instance, one potential application of nanosensors involves the utilisation of quantum dots for the purpose of detecting cancerous cells within the human body through injection. Quantum dots refer to crystalline structures composed of semiconductor materials with dimensions on the nanometer scale, which exhibit the unique property of emitting fluorescent radiation. The crystals utilised in this study consist of cadmium selenide (CdSe), cadmium sulphide (CdS), or indium gallium phosphide (InGaP). To ensure the safety of human cells, these crystals are coated with polymers that effectively mitigate the potential toxic effects of cadmium. Additionally, the polymer coating facilitates the attachment of specific molecules, enabling the tracking of cell processes and the identification of cancerous conditions. Undoubtedly, the realisation of such an application necessitates the advancement of nanosensor technology. The insertion of macro- or microsensors into the human body poses significant challenges due to potential harm or disruption to normal physiological functioning. The advantageous utilisation in this context stems from the diminutive dimensions of nanosensors. The exploration of futuristic advancements holds immense potential for the utilisation of nanosensors as diagnostic and therapeutic tools at the molecular level in the field of medicine. Additionally, these advancements can pave the way for the development of networks comprising nanorobots, enabling the real-time monitoring of various physiological parameters within the human body [17].

The emerging field of systems biology, which aims to investigate the fundamental principles governing living systems through the use of quantitative models of both inter- and intracellular processes, is in need of nanosensors and tools to gather data for the purpose of model validation. Implantable devices, such as autonomous nanorobots or multifunctional endoscopes, play a crucial role in various medical applications, including minimal invasive diagnostics, health monitoring, and drug delivery. These devices are designed to operate within the body and require ultraminiature sensors to effectively carry out their intended tasks while minimising invasiveness. One example of such a device is the multifunctional endoscope, which consists of a long, thin, flexible or rigid tube equipped with a light source and a video camera. This enables medical professionals to visualise the internal structures of a patient's body on a screen, aiding in accurate diagnosis and treatment. The development of these implantable devices and their associated ultraminiature sensors represents a significant advancement in medical technology, offering new possibilities for intra-corporal interventions and improving patient care. The foreseeable limitations in downscaling of conventional systems necessitate the emergence of novel materials exhibiting unique properties at the nanoscale. These materials will play a crucial role in meeting the sensor requirements of ultraminiaturized sensor systems [18].

1. Low Power Consumption

Historically, traditional sensors have been characterised by their substantial size and high power consumption. The metal oxide gas sensor is a notable example to be considered. The initial iteration of the device comprises a cylindrical structure composed of ceramic, a material known for its hardness, brittleness, high resistance to heat, and ability to withstand

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corrosion. Within this tube, a heater coil is securely positioned along the central axis. The outer surface of the ceramic tube was coated with a paste consisting of tin oxide (SnO_2) powder and palladium (Pd). The temperature of the tin oxide layer was elevated to a range of 200°C–500°C using the heater, thereby resulting in an increase in the sensitivity towards inflammable gases. The sensing principle revolves around the observed phenomenon of a reduction in resistance exhibited by tin oxide when exposed to an environment containing a combustible gas. During the operational phase, it is evident that the sensor exhibited power consumption in the range of several tens of watts. The subsequent iteration of sensors was comprised of a ceramic substrate. A Pt heater with a meander-shaped pattern was deposited on the underside of the substrate. The application of the tin oxide paste on the upper surface was accomplished through the utilisation of screen printing, a well-established printing technique that involves the utilisation of a woven mesh to support an ink-blocking stencil. In this process, a roller or squeegee is systematically moved across the screen stencil, thereby exerting pressure and facilitating the transfer of ink past the threads of the woven mesh in the open areas. The power consumption of this sensor was observed to be significantly lower in comparison to its predecessor, with a reduction of a few watts. The observation suggests that gas sensing does not necessitate a substantial quantity of material, as only a significant surface area is required. Additionally, a thick layer of sensing material is not essential for this purpose. Hence, a significant portion of the energy consumed for heating purposes is needlessly dissipated. The potential for significant power conservation may be realised through the implementation of a strategy aimed at diminishing the thermal mass of the sensor. The subsequent enhancement entailed the production of a downsized hotplate through the process of silicon micromachining. The hotplate, which was produced using Microelectromechanical Systems (MEMS) technology, exhibited a remarkably compact size, measuring merely 100µm×100µm. The thickness of the supporting plate, composed of a combination of silicon dioxide and silicon nitride, was measured to be 2µm. In order to reduce conduction losses, the hotplate was strategically suspended over a cavity. The hotplate under investigation, along with its associated sensor, exhibited minimal power consumption on the order of milliwatts. Nevertheless, it is important to note that the reduction in power consumption represents merely one facet among several factors that contribute to the motivation for downsizing sensors [19].

2. Faster response

The reduced size of sensors facilitates a more rapid attainment of equilibrium with the surrounding environment. This expedited process is primarily attributed to the decreased time required for signals to traverse shorter path lengths. Hence, it can be inferred that the utilisation of these sensors enables the execution of the intended operations at accelerated rates. The derivation of benefits from a fast speed is a subject of interest and inquiry. The examination of such benefits involves an exploration of the advantages that can be obtained through the attainment and maintenance of a high velocity. Measurements are conducted in real time, allowing for the collection of data that is promptly analysed to determine the appropriate course of action [20].

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3. Multi-Analyte Detection and Multifunctionality

In order to detect multiple gases, it is necessary to employ an array of gas sensors. The construction of an array comprising hundreds or even thousands of sensors presents a significant challenge due to the resulting size and cost implications. The sheer magnitude of such an array would render it highly impractical to fabricate and utilise in real-world applications. The utilisation of nanosensors presents a significant advancement in the field of real-time gas composition monitoring due to their enhanced multiplexing capability. A single device has the capability to incorporate an extensive array consisting of thousands of nanosensors. Each nanosensor is coated with a distinct functional group, thereby enabling it to be finely tuned to a predetermined analyte. The development of an ultraminiaturized and low-power device, combined with advanced signal-processing and pattern-recognition algorithms, holds great potential for effectively discriminating among various target analytes. This device has the ability to generate a distinct signature or fingerprint when exposed to a specimen that contains a combination of chemical and biological elements necessary for environmental pollution control. The aforementioned scenario bears resemblance to the evolutionary trajectory of computers throughout history. The early iterations of computers were characterised by their substantial size, necessitating dedicated rooms for their housing due to spatial constraints. These machines consumed significant amounts of electrical power and consequently generated substantial heat as a byproduct. The progression of technology has led to a reduction in size, resulting in the development of desktop personal computers, followed by laptops, and eventually palmtop computers. The progression observed in power consumption has yielded significant reductions, ultimately resulting in battery-operated computers achieving remarkably low levels of power consumption. Simultaneously, there was a notable enhancement in the computational capacities of computers. The rapid advancements in the field of microelectronics have facilitated this phenomenon, primarily driven by the remarkable progress achieved in the development of very-large-scale and ultra-large-scale integrated circuits (ICs). These groundbreaking technologies, known as Very-Large-Scale Integration (VLSI) and Ultra-Large-Scale Integration (ULSI), have played a pivotal role in enabling this progress. The concept of multifunctionality is a highly adaptable and versatile characteristic observed in various natural systems. The human tongue serves as a sensory organ for taste perception and plays a crucial role in the production of speech sounds. The human nose serves the dual functions of olfaction, or the sense of smell, and respiration, or the act of breathing. In a similar vein, it is worth noting that numerous other organs within the human body exhibit the capacity to fulfil multiple functions. Nanosensors are anticipated to exhibit multifunctionality as well.

4. Enhanced sensitivity

Numerous sensors operate by leveraging the phenomenon of adsorption, wherein target analytes are attracted and adhere to the sensor's surface. The extent of adsorption is contingent upon two key factors: surface area and surface chemistry. The utilisation of a nanoporous or nanocrystalline material in the fabrication of a sensor results in a substantial augmentation of the surface area. A notable illustration of this phenomenon is observed in the case of a single-walled carbon nanotube (SWCNT), which exhibits a surface area of 1600 m^2g^{-1}. The sensitivity of a gas sensor can be significantly enhanced by increasing the surface

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area. The utilisation of tin oxide (SnO_2), indium oxide (In_2O_3), antimony oxide (Sb_2O_3), or zinc oxide (ZnO) in the form of nanoparticles leads to a significant enhancement in sensitivity. In isolation, carbon nanotubes (CNTs) exhibit limited sensitivity towards analytes. However, through surface modification techniques such as appropriate coating or the introduction of palladium (Pd) atoms, their selectivity towards specific species can be enhanced. A diverse range of microelectronic platforms are manufactured. Several noteworthy examples in the field include the microhotplate, ion-sensitive field-effect transistor (ISFET), and microcantilever. The Ion-Sensitive Field-Effect Transistor (ISFET) is a variant of the Metal-Oxide-Semiconductor Field-Effect Transistor (MOSFET) that lacks the presence of a metal layer on its gate. Instead, the gate dielectric of the ISFET is composed of various materials such as silicon nitride (Si_3N_4), aluminium oxide (Al_2O_3), and tantalum pentoxide (Ta_2O_5). The pH sensor can be transformed into a specialised ion sensor or biosensor through the application of appropriate membranes on the gate. The aforementioned platforms possess an inherent lack of sensitivity towards any analyte or are only sensitive towards specific analytes. Consequently, it becomes necessary to apply appropriate coatings to enhance their sensitivity, thereby facilitating the creation of sensor families. Each platform can be considered as a distinct source of a sensor family.

5. **Easy interfacing with biomolecules**

Nanomaterials may easily create interfaces between biomolecules and readout devices because their sizes are equivalent to those of biomolecules such as proteins, viruses (a tiny infectious agent), cells, and nucleic acids (the building blocks of living creatures). Nanosensors take use of the parity or comparability in size between nanomaterials and biomolecules. On the interaction of nanomaterials with biomolecules, several nanosensors are built. They are referred to as nanobiosensors.

6. **Economical**

The achievement of low-cost products necessitates the miniaturisation of sensors and the integration of devices, which can be accomplished through reproducible fabrication processes and large-scale production. Nanosensors offer a promising avenue to fulfil these requirements, thereby enabling the development of more affordable devices. Consequently, conducting research on nanosensors holds the potential to significantly contribute to the realisation of cost-effective products. The current imperative is to ensure the widespread availability of disposable nanosensors at highly affordable prices.

7. **Possibility of a New Genre of Devices**

Nanosensors have revolutionised the field of device construction by enabling the development of a novel category of devices known as "intelligent sensors." These cutting-edge sensors possess the ability to perform data processing, storage, and analysis, thereby expanding the capabilities of traditional sensing technologies. The sensors under consideration exhibit exceptional qualities, including high accuracy, ultrahigh sensitivity, and extreme specificity. They are capable of providing real-time in vivo information with remarkable speed. Furthermore, these sensors offer the advantage of multi-analyte options, allowing for the simultaneous detection of multiple substances. Additionally, they require a smaller quantity of sample and necessitate minimal sample preparation. These sensors are designed to be durable, safe, and portable, making them highly practical for various

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applications. Certain devices belonging to the nanosensors generation have successfully undergone rigorous evaluation in controlled laboratory settings, thereby meeting the necessary criteria for their intended applications. Consequently, these devices have commenced their integration into the commercial market, becoming increasingly accessible to consumers. However, it is important to note that significant progress has been made, but it is crucial to acknowledge that there are still numerous challenges that need to be addressed in order to achieve the desired outcome. However, it is important to note that the potential of this phenomenon is vast. [21-23].

Definition and Classification of Nanosensors

Any sensor that operates by taking advantage of a nanoscale phenomenon is referred to as a nanosensor. Nanosensors are chemical or mechanical sensors that can be used to detect the presence of chemical species and nanoparticles, or monitor physical parameters such as temperature, on the nanoscale. They find use in medical diagnostic applications, food and water quality sensing, and other chemicals.

The nanosensors can be categorised according different criteria as follows

I] Classification of nanosensors based on dimension

i) the size of the sensor is in nanoscale, Nanosensors encompass the process of signal conversion from the surrounding environment through the utilisation of nanostructures. These nanostructures are characterised by having a lateral dimension of less than 100 nm and the other dimension less than 1 μm. Therefore, according to this definition, sensors are required to adhere to nanotechnology principles based on the sensor's geometrical dimensions. A nanowire refers to a slender filament composed of a specific material, such as a metal, with a diameter that measures below 100nm. Nanofibers are fibrous structures characterised by their submicron dimensions, typically ranging from 50 to 500 nanometers in diameter. Nanotubes are cylindrical structures with a hollow interior, possessing a diameter of a few nanometers, and composed primarily of a single elemental constituent, such as carbon. Nanobelts are nanostructures that exhibit a belt-like morphology. Nanoprobes are optical instruments designed for the purpose of visualising objects of minuscule dimensions. Quantum dots refer to fluorescent semiconductor crystals that possess nanoscale dimensions.

ii) sensitivity of the sensor is in the nanoscale, Sensors with varying dimensions, including both micro- and macro-scale sizes, can be classified as nanosensors when their sensitivities are measured in nano-units. For instance, a position or displacement sensor with sensitivity measured in nanometers (nm), a force sensor with sensitivity measured in nano-Newtons (nN), a temperature sensor with sensitivity measured in nano-Kelvin (nK), and a solution concentration sensor with sensitivity measured in nano-Molarity (nM), among others.

iii) the spatial interaction distance between the sensor and the object is in nanometers, wherein the spatial interaction distance between the examining electrode and the object under investigation is on the order of a few nanometers, for example atomic force microscope (AFM), are also nanosensors.

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II] Classification of nanosensors based on requirement of energy as follows

i) Active sensors: The aforementioned nanosensors belong to a class that necessitates an external energy source to operate effectively, for example, a thermistor, resistive strain gauge, etc.

ii) Passive sensors: It is a class of sensors that do not require the energy source, for example, a thermocouple, photodiode, piezoelectric sensor.

III] Classification according to the form of energy signal detected

i) Physical sensors: Nanosensors are employed for the purpose of quantifying various physical parameters such as temperature, pressure, flow, stress, strain, position, displacement, or force. Physical nanosensors, which belong to the category of nanoscale devices, exhibit exceptional capabilities in detecting and quantifying a wide range of physical properties with remarkable precision and sensitivity. The sensors under consideration function at the nanoscale, exhibiting the ability to detect and react to alterations in various physical parameters. This characteristic renders them highly advantageous for an extensive array of applications, as they furnish valuable data and insights.

ii) Chemical Nanosensors: Chemical nanosensors represent a distinct category of nanoscale devices that have been meticulously engineered to exhibit exceptional capabilities in detecting and quantifying the existence of particular chemicals or chemical reactions. These nanosensors possess an extraordinary level of sensitivity and selectivity, enabling them to discern and measure even minute quantities of target substances. The nanosensors under consideration possess the ability to detect alterations within the chemical milieu and offer prompt or nearly prompt data regarding the concentration or identification of specific molecules. The utilisation of these technologies spans across diverse domains, encompassing environmental monitoring, healthcare, food safety, and industrial processes, among others.

iii) Biological nanosensors: Biosensors have emerged as highly valuable instruments in the area of detecting and analysing biologically active substances. These substances encompass a wide range of cellular agents, including Yersinia pestis, a bacterium predominantly found in rodents, particularly rats, and known for its role in causing toxic plague. Another notable example is Bacillus anthracis, a bacterium that gives rise to anthrax and possesses the ability to form dormant endospores. These endospores are resilient structures akin to bacterial seeds, enabling the bacterium to enter a dormant state during unfavourable conditions. Upon inhalation, ingestion, or contact with a skin lesion on a host, the dormant bacteria can swiftly multiply and cause infection. Biosensors have demonstrated their applicability in the domain of supramolecular entities, including influenza viruses that display collective behaviour within organised molecular ensembles. Additionally, biosensors have been employed to detect molecular substances such as Staphylococcal enterotoxin B (SEB), a protein toxin released by the bacterium Staphylococcus aureus. Biosensors are commonly classified as a subset of chemical sensors in certain contexts [24-26]. The conversion phenomena of sensors are depicted in figure 2.

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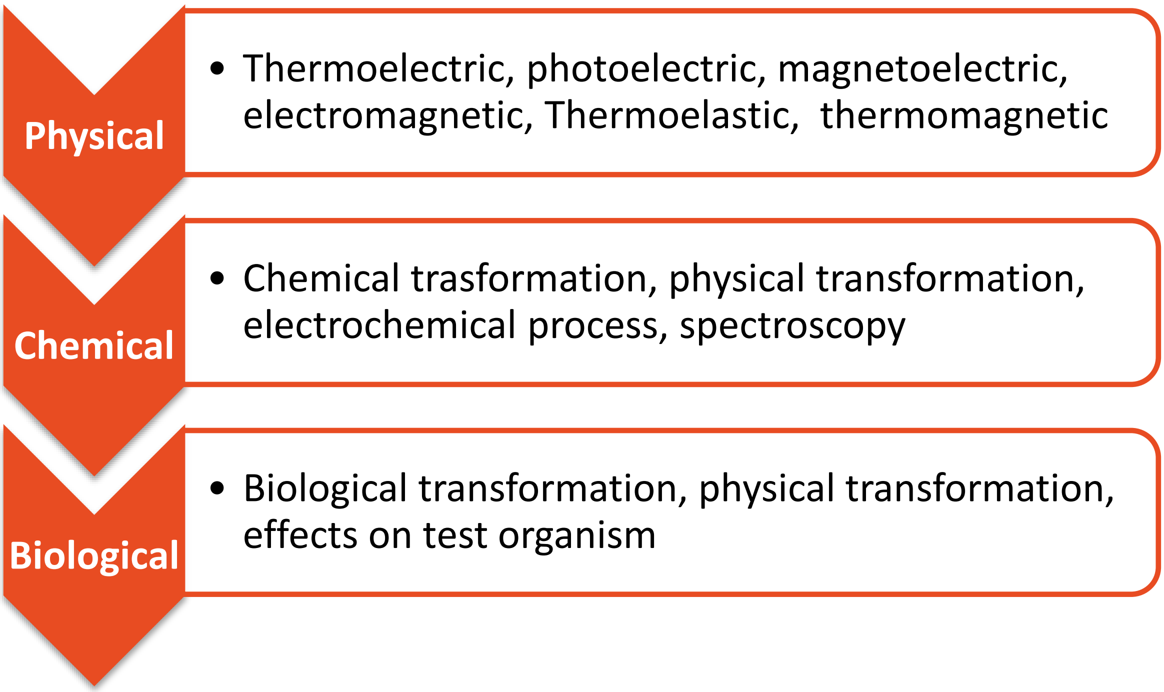

Figure 2: Conversion Phenomena of Sensor

Applications of Nanosensors

1. Medical diagnostics: Nanosensors are of paramount importance in the field of medical diagnostics, as they facilitate the timely identification of diseases and the provision of tailored healthcare solutions. Nanoscale biosensors have the capability to identify and analyse particular biomarkers present in bodily fluids, thereby facilitating the diagnosis of various diseases such as cancer, diabetes, and infectious diseases. These biosensors exhibit a remarkable level of sensitivity and specificity, enabling accurate and reliable detection.

Biomarker detection: Nanosensors possess the capability to discern and identify distinct biomarkers, including proteins, nucleic acids, and metabolites, which serve as indicative indicators of the existence or advancement of various diseases. The development of Localised Surface Plasmon Resonance (LSPR) biosensors by Chuang et al. has garnered significant interest in the field of point-of-care diagnosis for Mycobacterium tuberculosis. The present investigation employed DNA aptamers in conjunction with gold nanorods (Au NRs) to fabricate localised surface plasmon resonance (LSPR) platforms. These platforms were effectively utilised for the sensitive detection of interferon-gamma (IFN-γ) at a concentration as low as 0.1 nanomolar (nM). IFN-γ serves as a crucial biomarker associated with the diagnosis of latent tuberculosis infection. [27].

Infectious disease detection: Nanosensors possess the capability to detect and identify pathogenic microorganisms and viruses, thereby facilitating expedited and precise diagnosis of infectious diseases. Point-of-care testing and surveillance during disease outbreaks are areas where they play a crucial and indispensable role. The development of a graphene-based nanosensor for the detection of the Zika virus was undertaken by Afsahi et al. The researchers successfully quantified the concentration of Zika viral antigens, achieving a remarkably low

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measurement of 450 pM. A potential diagnostic tool was demonstrated in this study, wherein the researchers successfully detected Zika antigen in human serum samples. [28].

Imaging and contrast agents: Nanoscale imaging agents, such as quantum dots or iron oxide nanoparticles, have been found to significantly augment the sensitivity and resolution of various medical imaging techniques, including magnetic resonance imaging (MRI) and fluorescence imaging. These innovative technologies serve to enhance the visualisation of disease sites and enable real-time monitoring of drug delivery processes.

Quantum dots have been frequently employed as signal reporters in nanosensors due to their exceptional photostability in comparison to organic molecules [29]. One of the reasons for this phenomenon can be attributed to the fact that a quantum dot consists of a multitude of atoms, typically numbering in the tens of thousands. This results in a significantly higher degree of delocalized chemical bonding within the quantum dot structure. Consequently, the quantum dot exhibits an enhanced resistance to photon-induced damage when compared to individual fluorescent dye molecules [30]. In the past few years, there has been a growing interest in utilising quantum dot–based nanosensors for various in vitro sensing applications [31]. These applications include the detection and measurement of pH levels [32], calcium ion concentrations [33], and potassium ion concentrations [34]. In a ground-breaking study, Orte et al. successfully showcased the utilisation of photoluminescence decay time in functionalized quantum dots as a means to detect alterations in intracellular pH. This novel approach was coupled with fluorescence lifetime imaging microscopy (FLIM), leading to enhanced sensitivity in comparison to conventional pH fluorescent dyes. [32].

Theranostics: Some nanosensors have been specifically engineered for theranostic purposes, effectively integrating diagnostic and therapeutic functionalities within a single system. The concurrent detection of disease biomarkers and targeted delivery of therapeutic agents represents a significant advancement in the field. This innovative approach allows for precise and localised treatment, thereby minimising the occurrence of undesirable side effects. The utilisation of nanoparticles has been identified as a pivotal approach in three primary theranostic directions. The initial approach pertains to the assessment of treatment efficacy by utilising molecular imaging techniques, employing nanoparticles (NPs) as contrast agents. The objective of the second experiment is to evaluate the efficacy of a nanoparticle-based therapeutic approach through the utilisation of molecular imaging probes. The third description elucidates the multifunctionality of nanoparticles, which serve as both target therapy agents and molecular imaging tools simultaneously. In relation to this matter, the initial two procedures involve the NP system functioning as either the evaluator or the evaluated component. However, in the case of the last strategy, these roles exhibit an overlapping nature. The existence of each of these roles facilitates the advancement of prospective therapeutic interventions [35]. In a study conducted by H. Devalapalli et al., a group of researchers explored and investigated Poly(ethylene oxide)-modified poly(beta-amino ester) nanoparticles have been developed as a pH-sensitive system for the targeted delivery of hydrophobic drugs, specifically paclitaxel, to tumour sites [36].

Glucose monitoring: Nanosensors find application in a variety of continuous glucose monitoring devices, which are designed to cater to the needs of individuals afflicted with diabetes. Glucose levels in interstitial fluid are measured, enabling individuals to engage in

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continuous monitoring of their blood sugar levels and subsequently make appropriate modifications in insulin dosing or lifestyle as required.

The utilisation of carbon nanotubes (CNTs) in glucose monitoring has garnered significant attention, primarily owing to their distinctive electrical characteristics, compatibility with biological systems, and substantial surface area. These attributes collectively enable the detection of glucose in biological fluids with heightened sensitivity and specificity.

The utilisation of carbon nanotubes (CNTs) for glucose monitoring has been demonstrated in various studies. It involves the following steps-

Functionalization: The surface of carbon nanotubes is functionalized with glucose oxidase (GOx) enzymes. Glucose oxidase is an enzyme that catalyzes the oxidation of glucose to produce gluconic acid and hydrogen peroxide. The functionalization process helps in immobilizing the enzyme on the CNT surface and improving the sensitivity and selectivity of the sensor.

Glucose Detection: When the CNTs with immobilized GOx are exposed to a glucose-containing solution (e.g., blood or interstitial fluid), glucose molecules in the sample react with the enzyme. This reaction produces gluconic acid and hydrogen peroxide.

Electrical Measurement: Carbon nanotubes exhibit electrical conductivity, and the presence of hydrogen peroxide alters the electrical properties of the CNTs. This change in electrical conductivity can be measured and correlated with the glucose concentration in the sample.

Calibration: Before using the sensor for glucose measurement, a calibration curve is typically constructed to establish a relationship between the measured electrical signal and the actual glucose concentration. This calibration process ensures accurate glucose quantification.

Continuous Monitoring: In some cases, the CNT-based glucose sensors can be integrated into wearable devices or implanted in the body to enable continuous glucose monitoring for individuals with diabetes or other glucose-related conditions [37].

Drug delivery monitoring: The integration of nanosensors within drug delivery systems enables the real-time monitoring of drug release dynamics and subsequent distribution within the human body. The provided data facilitates the optimisation of drug dosage and guarantees accurate drug administration to the intended location.

Tang et al. reported a novel approach for drug delivery utilising a fluorescence resonance energy transfer (FRET) mechanism. This approach involved the direct coupling of Polyethylene glycol (PEG) onto the surface of Carbon Dots (CDs), followed by the entrapment of Doxorubicin (a guest drug molecule) within the PEG network. The attachment of the drug-loaded PEG network to the CD surface was achieved through π-π stacking interactions. This unique design enabled the real-time monitoring of drug release by leveraging the fluorescence resonance energy signal. In the present example, the spatial arrangement of Carbon Dots, which exhibit remarkable capabilities as drug carriers, and Doxorubicin, acting as the acceptor molecule, resulted in the formation of a Förster resonance energy transfer (FRET) pair. Upon excitation of the Carbon Dots at a wavelength of 405 nm, two distinct emissions were observed at 498 nm and 595 nm. The emission at 498 nm can be attributed to the intrinsic emission of the Carbon Dots themselves, while the emission at 595 nm is indicative of energy transfer occurring from the Carbon Dots to Doxorubicin. Upon the release of Doxorubicin molecules from the surface of Carbon Dots within an acidic

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environment, it can be observed that the Förster resonance energy transfer (FRET) between the Carbon Dots and Doxorubicin ceases (FRET off), resulting in a noticeable increase in emission intensity at a wavelength of 498 nm. The observed modulation of the Förster resonance energy transfer (FRET) signal can be effectively governed through the controlled liberation of therapeutic compounds from the surface of Carbon Dots. Consequently, this enables facile visualisation of cellular structures and facilitates the direct, temporal assessment of drug release kinetics. [38].

2. Environmental monitoring: Nanosensors have been widely employed in the field of environmental monitoring to effectively assess various parameters, including but not limited to air and water quality, soil contamination, and pollutant levels. Real-time data is furnished by these systems to evaluate the state of the environment in terms of its health and to assist in the implementation of measures aimed at controlling and mitigating pollution [39].

Air quality monitoring: Nanosensors have the capability to identify and measure various air pollutants, including particulate matter (PM), volatile organic compounds (VOCs), carbon monoxide (CO), nitrogen oxides (NOx), and ozone (O3). Portable devices have been developed to enable real-time monitoring of air quality in various settings such as urban areas, industrial sites, and indoor environments. These devices are designed to be integrated seamlessly into different portable platforms, allowing for continuous and convenient monitoring of air quality parameters. The development of a low temperature CO gas-sensor utilising SnO2 Quantum Dots was carried out by S. M. Sedghi et al. The observed response to carbon monoxide (CO) exhibits a notable increase throughout the entire temperature spectrum, ranging from 25 to 300 °C. This response is found to be several magnitudes greater than that exhibited by conventional sensors [40].

Water quality monitoring: Nanosensors are utilised in the field of environmental monitoring to detect various contaminants present in water bodies. These contaminants encompass a wide range of substances such as heavy metals, pesticides, and organic pollutants. By employing nanosensors, researchers are able to accurately identify and quantify the presence of these harmful substances in water, thereby facilitating effective monitoring and management strategies for maintaining water quality. Continuous monitoring systems have the capability to facilitate the ongoing assessment of water quality in various aquatic environments, including lakes, rivers, and sources of drinking water.

The development of a cantilever nanobiosensor by Rigo et al. is noteworthy, as it has been functionalized with urease enzyme through the process of self-assembling monolayers. This innovative approach allows for the detection of heavy metals such as lead, nickel, cadmium, zinc, cobalt, and aluminium in water. The differential responses observed by the authors in relation to varying concentrations of heavy metals and ultrapure water indicate the potential of ultrapure water as a medium for detecting the presence of heavy metals. The nanobiosensor exhibited notable attributes such as elevated sensitivity, commendable stability, and a detection limit within the parts per billion (ppb) range, even after a storage period of 30 days [41].

Soil and sediment analysis: Nanosensors have been employed for the purpose of evaluating soil and sediment contamination, enabling the detection of various pollutants such as heavy

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metals, petroleum hydrocarbons, and pesticides. Soil health evaluation and identification of potential environmental risks are facilitated by their utilisation [42].

Greenhouse gas monitoring: Nanosensors possess the capability to quantitatively detect and analyse greenhouse gases, including carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). These nanoscale devices are employed for the purpose of monitoring greenhouse gas emissions and evaluating the consequential effects on climate change [43].

Food safety: Nanosensors are employed in the context of food safety and quality to effectively identify and detect contaminants present in food products. By leveraging the unique properties and capabilities of nanotechnology, these sensors play a crucial role in ensuring the integrity and reliability of our food supply chain. The ability to detect and identify pathogenic bacteria, harmful toxins, and chemical residues plays a crucial role in mitigating the risk of foodborne illnesses and enhancing the management of the food supply chain [44].

3. Drug delivery: Nanosensors play a crucial role in drug delivery systems by facilitating the monitoring of drug release dynamics and assessing drug efficacy. Drug delivery can be effectively monitored in real-time, thereby facilitating precise dosing and mitigating the likelihood of adverse reactions. [45].

4. Wearable health devices: Nanosensors have been successfully incorporated into wearable health devices, including but not limited to fitness trackers and smartwatches, with the primary objective of monitoring various physiological parameters such as vital signs, physical activity levels, and sleep patterns. These devices serve as valuable tools for individuals, enabling them to access crucial health information for the purpose of self-monitoring and enhancing their overall well-being. [46].

5. Smart textiles: Nanosensors have been successfully integrated into various fabric materials, leading to the development of smart textiles. These innovative textiles possess the ability to effectively monitor crucial parameters such as body temperature, hydration levels, and even environmental conditions. The utilisation of these textiles is observed across various sectors, including athletics, the armed forces, and the medical field [47].

6. Industrial processes: Nanosensors find utility within industrial environments for the purpose of process control and surveillance. The organisms possess the ability to perceive alterations in temperature, pressure, and chemical concentrations, thereby facilitating the achievement of optimal and secure operational conditions [48].

7. Water quality monitoring: Nanosensors have been widely utilised for the purpose of evaluating water quality across diverse environments, encompassing drinking water sources, wastewater treatment facilities, and natural aquatic ecosystems. Contaminants and pollutants can be detected at low concentrations by these organisms [49].

8. Nanomedicine: Nanosensors have been widely employed in the field of nanomedicine to facilitate precise drug delivery, enable advanced imaging techniques, and support the emerging field of theranostics, which integrates therapeutic interventions with diagnostic capabilities. Precision medicine approaches have been found to enhance the efficacy of disease treatment by enabling more precise and targeted interventions [50].

9. Internet of Things (IoT): The integration of nanosensors into Internet of Things (IoT) devices has emerged as a significant development in the field, facilitating the progress of

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smart cities, smart homes, and interconnected systems. The primary objective of data collection in this context is to enhance the processes of robotics, productivity, and making choices. [51].

Conclusion:

Nanosensors are used in a wide range of fields across many disciplines, including physics, biochemistry, materials science, biology, electrical engineering, and others. This can look at many fundamental ideas that govern nanomaterials and nanotechnology as well as their critical function in novel sensing attributes and implementations. The investigation of nanosensors involves the exploration of fundamental physical distinctions. This cutting-edge technology delves into intriguing multifaceted knowledge in science and technology, specifically at the level of the nanoscale. Nanosensors facilitate the exploration of chemical and biological processes at a highly refined level and within the realm of various dimensions. Nanoparticles have the potential to be employed in the construction of gas/vapour sensors, which could be miniaturised to the size of an ultrasonic stamp. Additionally, they can be utilised in the development of laboratory-on-a-chip biosensors, enabling the monitoring of water quality and health. Significant advancements have been made in the realm of nanosensors and optical nanotechnology, owing to their inherent dimensions and distinctive optical, magnetic, catalytic, and mechanical properties. Various operating mechanisms, including those based on biological and chemical principles, are employed to facilitate the transfer of nanoparticle information to the macroscopic environment. These technologies find their primary applications in the fields of health, biomedical research, and nanoscale industries, as well as in the manufacturing of various other nanoproducts. The integration of nanosensors within diverse bio-fabrication methodologies exhibits a synergistic effect on tissue generation. Advancements in the field of bioprinting science and technology hold the potential to augment the fabrication of nanosensors, enabling their utilisation in increasingly intricate and ambitious applications.

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